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# Time Dependence and Temperature Stability of the Permanent Magnets for the Fermilab Antiproton Recycler Ring

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**Abstract** The Fermilab Recycler Ring, part of the Main Injector upgrade<sup>i</sup>, is an 8 GeV storage ring consisting of 362 gradient magnets, 109 quadrupoles, 8 mirror magnets, and 5 Lambertsons. The field is driven by strontium ferrite permanent magnets and shaped by precision pole pieces. Temperature dependence of the ferrite is compensated by the use of Ni (30%) Fe (70%) alloy operating near its Curie point. Temperature stability is held to within 0.004%/°C rms. over the operating range of 25 to 35 C. Tighter stability requirements (0.001%/°C) for the high beta quadrupoles are met by active thermal control using heating blankets. Longitudinal uniformity is obtained by distribution of the compensator and ferrite throughout the magnet. Field strength in the magnets are adjusted to be within 0.05% of the design field. The Higher harmonics contribute less than 0.01% of the primary field measured at a radius of 25.4 mm. For the gradient magnets custom end shims are made to adjust the harmonics; the field is adjusted by adding or subtracting ferrite. The loss of magnetization is logarithmic in time with a  $\Delta(M_2/M_1) = 9.0 \times 10^{-4} \cdot \log(t_2/t_1)$ , corresponding to a 0.35% loss of field over the expected operating life of 20 years.

## I. Gradient magnets

An overview of the magnet design is presented elsewhere<sup>ii</sup>. In brief, there are four types of gradient magnets, focusing and defocusing, with pole lengths of 3.1 and 4.5 meters. Each has different quadrupole and sextupole fields. The basic design consists of precision shaped pole tips and pole spacers with strontium ferrite bricks on the outside of the poles. The entire package is surrounded by 0.75 inch thick flux return. A typical cross section is shown in Figure 1. A standard brick size of 4 inch by 6 inch by 1 inch is used. The easy axis is orientated along the

one inch thickness. Two bricks are used on each side between the pole and flux return to generate the required field. We define one unit of error as  $1 \times 10^{-4}$  (0.01%) of the field.

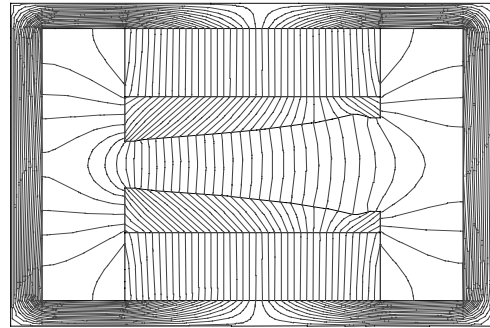


Figure 1

## II. Temperature Compensation

It is well known that the residual magnetic field ( $B_r$ ) of permanent magnets varies with temperature. To determine the precise value, a 40-inch quad (RQE005) was built with ferrite only, no compensator material. The magnet was frozen for 48 hours mounted on the MP-9 test stand in an insulated box (R-value of 13) and

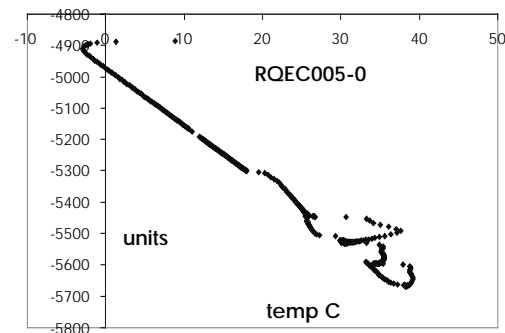


Figure 2

allowed to warm slowly for a period of 4 days. The gradient and harmonics were measured every 20 minutes during the entire time. Heat was applied and the magnet warmed to 38 °C.

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Figure 2 shows the warming cycle. A linear regression gives a slope of  $0.18\%/^{\circ}\text{C}$  ( $18.4 \text{ units}/^{\circ}\text{C}$ ). The deviations from a straight line are due to the heat transfer properties of the ferrite bricks. To lessen the impact of temperature variation, strips of a high nickel steel Ni (30%) Fe (70%) were inserted between the ferrite bricks to act as flux shunts (compensator) in the magnets. The strips made contact with both the pole and the flux return. The compensator has a Curie point between  $45$  and  $50^{\circ}\text{C}$ . When cold it behaves similar to iron (high permeability) and shunts flux out of the magnet gap. When warm the material has permeability closer to unity and allows more flux in the gap. The volume ratio of compensator material to ferrite was empirically determined for each type of magnet. Figure 3 shows the temperature dependence of the same magnet rebuilt with the proper amount of compensator strips. Note change of scale by a factor of 300.

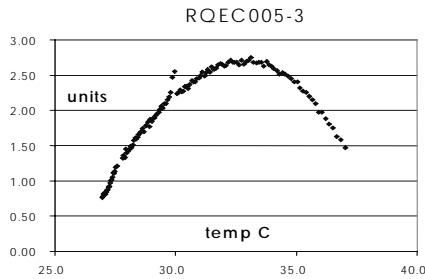


Figure 3

Due to chemical variations, heat treating and subsequent handling the Curie point of each batch of compensator varied. The compensator strips were mixed in a random pattern to distribute these variations. The exact numbers of strips for each magnet were determined empirically and monitored during production. The variation of field with temperature for each magnet was held to  $\pm 0.01\%/^{\circ}\text{C}$  ( $\pm 1.0 \text{ unit}/^{\circ}\text{C}$ ) with an rms of 0.004%.

The 40-inch quads are used in the high beta insert region. The requirements for gradient and temperature compensation were a factor of ten more stringent. Given the day to day and seasonal variation of the tunnel, it was impossible to achieve this with compensator strips alone. The 40-inch quads use electric blankets with a feedback loop to maintain the magnets at  $32 \pm 1^{\circ}\text{C}$ . Before installation in the tunnel each magnet was installed in an insulated box and warmed overnight to  $32^{\circ}\text{C}$ . The

gradient and other harmonics were then adjusted to the specified value. After installation in the tunnel the quads were surrounded by heating blankets and warmed back to  $32^{\circ}\text{C}$ .

### III. Longitudinal Flatness

Longitudinal non-uniformity for electromagnets is dominated by the gap since the coils serve to drive the flux. For permanent magnets, the strength is controlled by the integrated brick strength, with 1% brick variations; the total brick volume varies. The number of bricks and their placement can produce longitudinal non-uniformities (as much as 20%). Strength is controlled by sorting bricks on strength and adjusting the total volume (suing pieces as small as  $0.5 \times 0.5 \times 6$  inch) Uniformity was adjusted by brick and compensator density and longitudinal placement.

The uniformity of the intergal bend and the bend center of the magnet determine the orbit of the storage ring. These are set by the distribution of the dipole field. Since the lattice beta function is not uniform over the length of these magnets the focusing properties are related to intergal field, the first and second moments of the focusing field. The ratio of the dipole to quadrupole field is set by the precision of the pole shape. Measurement of the longitudinal distribution of the dipole field is sufficient to provide the quadrupole longitudinal shape. Algorithms for

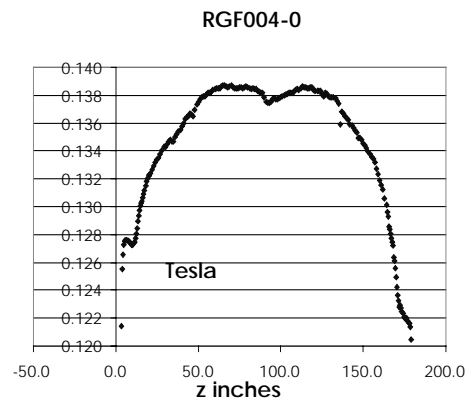


Figure 4

strength tuning were developed to achieve suitable intergal field and longitudinal shape. The ideal magnet would have a sharp rise in field at the beam entrance and an equally sharp turn off at the exit. Due to flux losses at the ends this does not happen. Studies were conducted on the

distribution of strips of temperature compensator in the magnet. On average 11 strips were required per pair of ferrite bricks. Figure 4 shows the field versus distance along the magnet with equal number of strips for each brick pair.

A test was done where all the compensator strips were located in the middle half of a magnet. There were no strips at either end. Measurements showed that the total temperature compensation and the piece wise temperature compensation were within

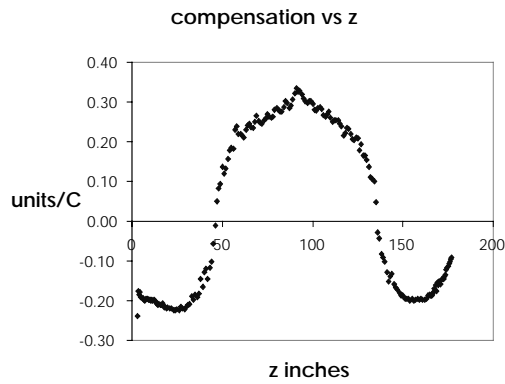


Figure 5

specified limits (Figure 5). The number of compensator strips between brick pairs and the position of the brick pairs were varied to create a smoother longitudinal field. More strips were located at the quarter points and less in the middle and ends. The long gradient magnet has 38 slots for compensator. The 11 slots on either side of the center contained 11 strips. The next 5 on either side of center contained 12 strips and the last 3 slots contained 10 strips. Aluminum spacers were also used to position the bricks and compensator packs along the pole piece. This served to keep the magnetic length similar for all magnets of a given series. Figure 6 shows a production magnet with a flattened profile. In cases where the  $B_r$  of the ferrite bricks was higher than normal more spacers were used to keep the magnetic length the same.

An automated Hall probe system was used to measure the longitudinal field at the centerline of each magnet. The first and second moments were calculated with respect to the mechanical center. The first moment was reported as the z center offset. This value was used to determine the longitudinal position during installation. The second moment was normalized to an ideal

magnet with a flat distribution and the fractional deviation from 1 was reported. Figure 7 shows the z centers for the 2 series of magnets. Figure 8 shows the second moment distributions. Table 1 provides the mean values and sigmas for the first and second moment. In a few cases the magnets were rebuilt to adjust the bend center.

	$\langle z \text{ offset} \rangle$ mm	$\sigma$	$\langle \Delta 2^{\text{nd}} \text{ moment} \rangle$	$\sigma$
RGF	-3.40	7.62	0.0206	0.0085
RGD	10.83	9.51	0.0094	0.0093
SGF	-2.98	7.09	-0.0039	0.0070
SGD	13.72	7.08	-0.0119	0.0087

Table 1

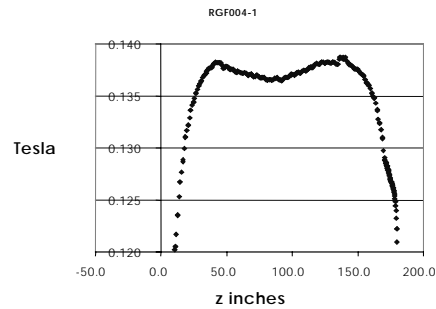


Figure 6

#### IV. Time Dependence of Fields

RGF005 was the first gradient magnet to fully meet all specifications for the Recycler ring. The ferrite was magnetized on November 11, 1997 and the magnet was assembled on November 13<sup>th</sup> and 14<sup>th</sup> 1997. On November 20<sup>th</sup> 1997 the temperature compensator strips were re-arranged to produce a flatter longitudinal field. Starting on February 2<sup>nd</sup> 1998 the magnet was measured every week for five months during gradient production. From April 22<sup>nd</sup> 1999 until July 29<sup>th</sup> 1999 RGF005-1 was measured every 20 minutes using a Morgan coil. Figure 9 shows the magnet temperature versus the relative field (brel) in units. A linear regression yields a slope of 0.8 units/ $^{\circ}\text{C}$ . The width of the curve indicates the temperature variation of the integrator.

The magnet was exposed to the normal day night temperature cycles of the building. Using the 0.8 units/ $^{\circ}\text{C}$  temperature coefficient the measurements were normalized to 20  $^{\circ}\text{C}$ . Figure 10 shows time versus nominal field deviation (brel) for April through June 1999.

The day night temperature cycle is clearly visible. A plot of brel versus the natural log of day since magnetization (Figure 10) has a slope of  $-9.0 \times 10^{-4}$ . This extrapolates to a 0.35% (35 units) loss of field over 20 years.

This loss will not degrade the operation of the storage ring. As of September 1999 all ring components have been installed and beam has been successfully circulated.

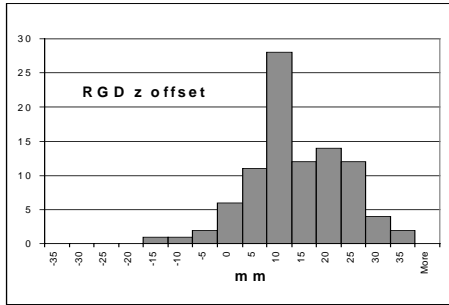


Figure 7a

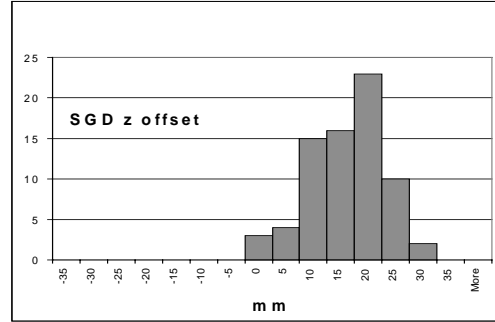


Figure 7b

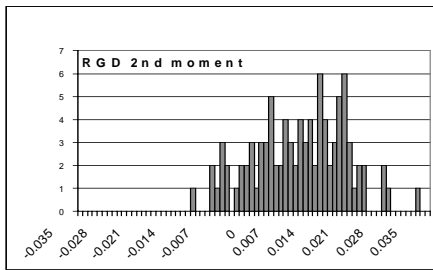


Figure 8a

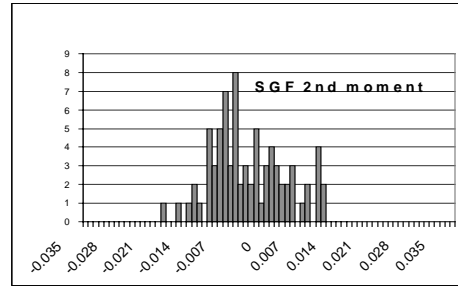


Figure 8b

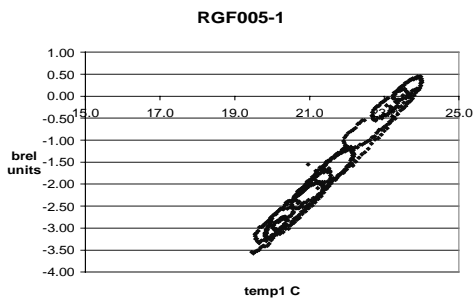


Figure 9

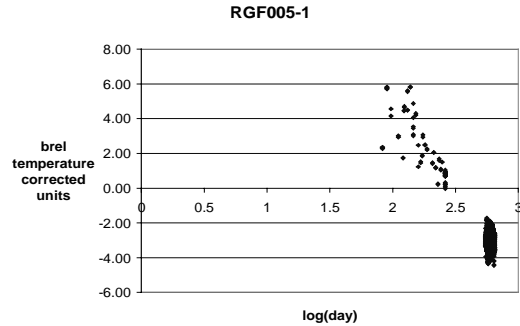


Figure 10

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